CLAIMS

1. An optical waveguide, comprising:

a core, comprising an elongate region of relatively low refractive index;

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light including an operating wavelength of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that the boundary is substantially anti-resonant at the operating wavelength of light.

2. An optical waveguide, comprising:

a core, comprising an elongate region of relatively low refractive index;

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 95% of the guided light is in the regions of relatively low refractive index in the waveguide.

3. A waveguide as claimed in either preceding claim, in which the boundary has a thickness such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 1% of the guided light is in the regions of relatively low refractive index in the photonic bandgap structure.

4. A waveguide as claimed in any preceding claim, in which the boundary has a thickness such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 50% of the guided light is in the region of relatively low refractive index in the core.

5. A waveguide as claimed in any preceding claim, in which the boundary has a thickness such that, in use, light guided by the waveguide is guided in a transverse mode

providing an F-factor of less than $0.23\mu m^{-1}$ for an operating wavelength of $1.55\mu m$, less than an equivalent F-factor value scaled for a different operating wavelength or less than $0.7\Lambda^{-1}$ for structures having a periodic cladding and a pitch Λ.

6. An optical waveguide, comprising:

a core, comprising an elongate region of relatively low refractive index;

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than $0.23\mu m^{-1}$ for an operating wavelength of $1.55\mu m$, less than an equivalent F-factor value scaled for a different operating wavelength or less than $0.7\Lambda^{-1}$ for structures having a periodic cladding and a pitch Λ.

7. A waveguide according to any one of claims 2 to 6, in which the boundary is anti-resonant at an operating wavelength of light.

8. A waveguide according to any one of the preceding claims, in which the boundary is a reflector.

9. A waveguide as claimed in any preceding claim, in which the boundary has a substantially constant thickness around the core.

10. A waveguide as claimed in any one of claims 1 to 8, in which the boundary has a thickness that varies around the core.

11. A waveguide as claimed in claim 10, in which the boundary has a thickness that varies periodically around the core.

12. A waveguide as claimed in claim 10 or claim 11, wherein the core boundary has a thickness t around at least a proportion y of the boundary, where $y > 0.5$.

13. A waveguide as claimed in any preceding claim, in which, in the transverse cross section, the photonic bandgap structure comprises an array of the relatively low refractive index regions separated from one another by the relatively high refractive index regions.

14. A waveguide as claimed in claim 13, in which the array is substantially periodic.

15. A waveguide as claimed in claim 13 or claim 14, in which the array is a substantially triangular array.

16. A waveguide as claimed in any preceding claim, in which at least two of the higher index regions in the photonic bandgap structure are connected to each other.

17. A waveguide as claimed in claim 16, in which the higher index regions in the photonic bandgap structure are interconnected

18. A waveguide as claimed in any preceding claim, in which the photonic bandgap structure comprises an arrangement of isolated relatively low refractive index regions separated by connected regions of relatively high refractive index.

19. A waveguide as claimed in claim 18, in which the connected regions of relatively high refractive index comprise an array of veins, each vein being connected at each end thereof to a node, which, in turn, is connected to at least two other veins.

20. A waveguide as claimed in claim 19, in which each vein has a characteristic thickness substantially at its mid-point between the two nodes to which it is connected.

21. A waveguide as claimed in any preceding claim, in which the boundary comprises, in the transverse cross-section, a plurality of relatively high refractive index boundary veins connected end-to-end around the boundary between neighbouring boundary nodes, each boundary vein being connected between a leading boundary node and a following boundary node, with no nodes in between, and each boundary node being connected between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure.

22. A waveguide according to claim 21, wherein each boundary vein has a characteristic thickness substantially at the mid-point between the two boundary nodes to which it is connected.

23. A waveguide according to claim 22, wherein more than a half of the boundary veins have a characteristic thickness at their mid-points, which is substantially the thinnest region along the vein.

24. A waveguide according to claim 22 or claim 23, wherein the characteristic thickness of at least one boundary vein is at least 110% of the characteristic thickness of a plurality of the veins in the array of veins in the photonic band-gap structure.

25. A waveguide according to any one of claims 22 to 24, wherein the characteristic thickness of a plurality of the boundary veins is at least 110% of the characteristic thickness of a plurality of the veins in the array of veins in the photonic band-gap structure.

26. A waveguide according to any one of claims 22 to 25, wherein the characteristic thickness of at least a majority of the boundary veins is at least 110% of the characteristic

thickness of at least a majority of the veins in the array of veins in the photonic band-gap structure.

27. A waveguide according to any one of claims 22 to 26, wherein the boundary veins are at least 180% of the characteristic thickness of the veins in the array.

28. A waveguide according to claim 22 or claim 23, wherein substantially all of the boundary veins are thicker than substantially all of the veins in the photonic band-gap structure.

29. A waveguide as claimed in any one of the preceding, in which the array has a characteristic primitive unit cell and a pitch Λ.

30. A waveguide as claimed in claim 29, in which the boundary has a thickness t, wherein, $t = u\Lambda$ for a proportion of the boundary y, where $u > 0.06$ and $y > 0.5$.

31. A waveguide as claimed in any one of claims 1 to 23, in which the core boundary has a thickness t defined by

$$\frac{a\lambda}{4\sqrt{n_{HI}^2 - n_{LO}^2}} \leq t \leq \frac{b\lambda}{4\sqrt{n_{HI}^2 - n_{LO}^2}},$$ where a=0.5 and b=1.75 and n_{HI} and n_{LOW} are the refractive indices of the boundary and of the relatively low refractive index region of the core, respectively.

32. A waveguide as claimed in any preceding claim, in which the core has, in the transverse cross-section, an area that is significantly greater than the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

33. A waveguide as claimed in claim 32, in which the core has, in the transverse cross-section, an area that is greater than twice the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

34. A waveguide as claimed in any preceding claim, in which the core has, in the transverse cross-section, an area that is greater than the area of each of the relatively low refractive index regions of the photonic bandgap structure.

35. A waveguide as claimed in any preceding claim, wherein the core has, in the transverse cross-section, a transverse dimension that is greater than the pitch Λ of the photonic band-gap cladding

36. A waveguide as claimed in any one of the preceding claims, in which at least some of the relatively low refractive index regions have a refractive index below 1.4.

37. A waveguide according to claim 36, in which at least some of the relatively low refractive index regions have a refractive index below 1.1.

38. A waveguide as claimed in any preceding claim, in which at least some of the relatively low refractive index regions are voids filled with air or under vacuum.

39. A waveguide as claimed in any one of claims 1 to 37, in which at least some of the relatively low refractive index regions are voids filled with a liquid or a gas other than air.

40. A waveguide as claimed in any preceding claim, in which at least some of the relatively high refractive index regions comprise silica glass.

41. A waveguide as claimed in any preceding claim, in which the relatively low refractive index regions make up more than 75% by volume of the photonic bandgap structure.

42. An optical fibre comprising a waveguide according to any one of the preceding claims.

43. An optical fibre as claimed in claim 42, wherein the loss of the optical fibre is less than 12dB/km.

44. An optical fibre as claimed in claim 43, wherein the loss of the optical fibre is less than 5dB/km.

45. An optical fibre transmission system comprising a transmitter, a receiver and an optical fibre, as claimed in any one of claims 42 to 44, for transmitting light between the transmitter and the receiver.

46. Data conditioned by having been transmitted through a transmission system as claimed in claim 45.

47. A method of forming elongate waveguide, comprising the steps:

forming a preform stack by stacking a plurality of elongate elements;

omitting, or substantially removing at least one elongate element from an inner region of the stack; and

heating and drawing the stack, in one or more steps, into a waveguide of a type described above as being according to the invention.

48. A method of forming elongate waveguide for guiding light, comprising the steps:

simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index and a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core,

wherein properties of the boundary region are represented in the computer model by parameters;

finding a set of values of the parameters that, according to the model, increases or maximises how much of the light guided by the waveguide is in the regions of relatively low refractive index in the waveguide; and

making a waveguide using the values.

49. A method of forming elongate waveguide for guiding light, comprising the steps:

simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index and a photonic bandgap structure arranged to provide a photonic bandgap over a range of frequencies of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core wherein properties of the boundary region are represented in the computer model by parameters;

finding a set of values of the parameters that, according to the model, decreases or minimises the F-factor of the waveguide; and

making a waveguide using the values.

50. A photonic crystal fibre, comprising:

an elongate, relatively low refractive index core;

an elongate photonic bandgap structure surrounding the core and comprising, in the transverse cross section, a lattice of relatively low refractive index regions separated by connected relatively high refractive index regions; and

a concentric boundary region, at the interface between the core and the photonic bandgap structure, the core boundary region being generally thicker around its circumference than regions of relatively high refractive index in the photonic bandgap structure.

51. A photonic crystal fibre, comprising:

a hollow core surrounded by a microstructured cladding, for providing a photonic band-gap at an operating wavelength of the fibre, the cladding comprising an array of elongate holes embedded in a solid matrix material, the fibre further comprising a solid boundary at the interface between the core and cladding, the boundary being substantially antiresonant at the operating wavelength of the fibre, whereby light at the operating

wavelength of the fibre is substantially confined to the core by virtue of both the boundary and the cladding.